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CORE/CORONA MODELING OF DIODE-IMPLODED ANNULAR LOADS,(U)

NOV 80 R E TERRY, J U GUILLORY DNA001-79-C-0189

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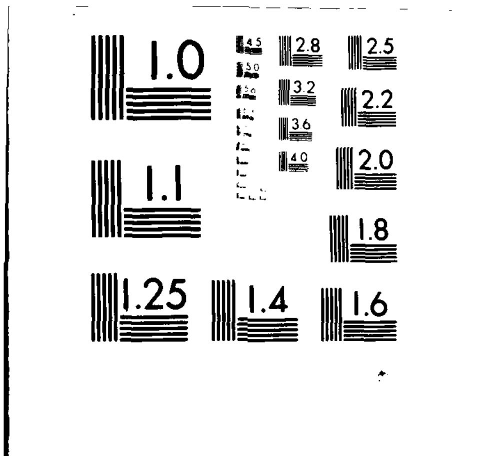

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CORE/CORONA MODELING OF DIODE-IMPLODED ANNULAR LOADS

(10 R. E. Terry [redacted] Guillory JAYCOR, Alexandria, VA.
John U.

The effects of a tenuous exterior plasma corona with anomalous resistivity on the compression and heating of a hollow, collisional aluminum z-pinch plasma are predicted by a one-dimensional code. As the interior ("core") plasma is imploded by its axial current, the energy exchange between core and corona determines the current partition. Under conditions of rapid core heating and compression, the increase in coronal current provides a trade-off between radial acceleration and compression, which reduces the implosion forces and softens the pinch. Combined with an heuristic account of energy and momentum transport in the strongly coupled core plasma (~~typically~~ $\lambda_{ii} \sim 0.1$) and an approximate radiative loss calculation including Al line, recombination and Bremsstrahlung emission, the current model can provide a reasonably accurate description of imploding annular plasma loads that remain azimuthally symmetric. The implications for optimization of generator load coupling are examined.

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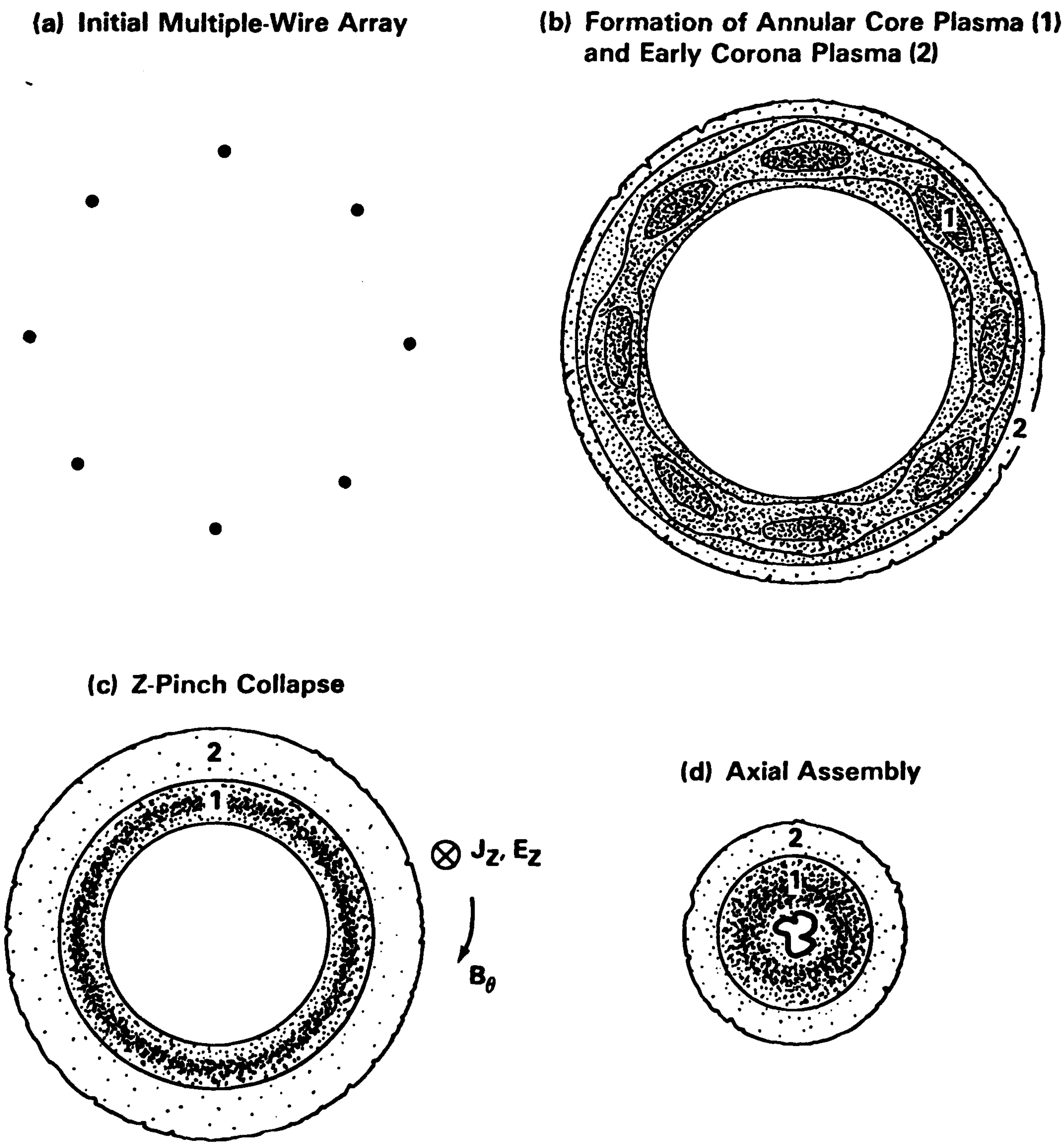
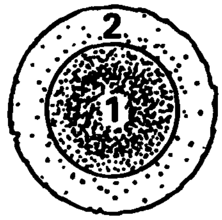


- Growth of Coronal Current, I_2
- Compression and Heating of Core Plasma
- Decay of Core Current, I_1, and Resultant Softening of the Pinch

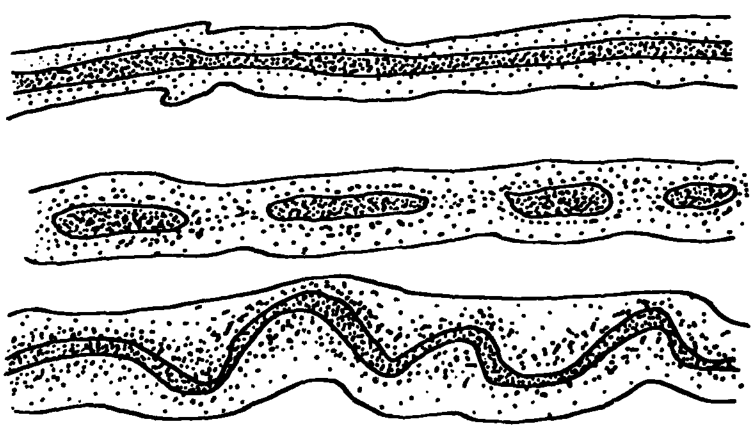
- Sharp Growth of I_2, Compression and Heating in the Core Plasma

(e) Peak Compression



- $T_1 \sim 0.5$ keV, $n_1 \sim 10^{20}$ cm^{-3}
- Reversal of Inward Momentum
- Peak of I_2, T_2

(f) Late Time Behavior



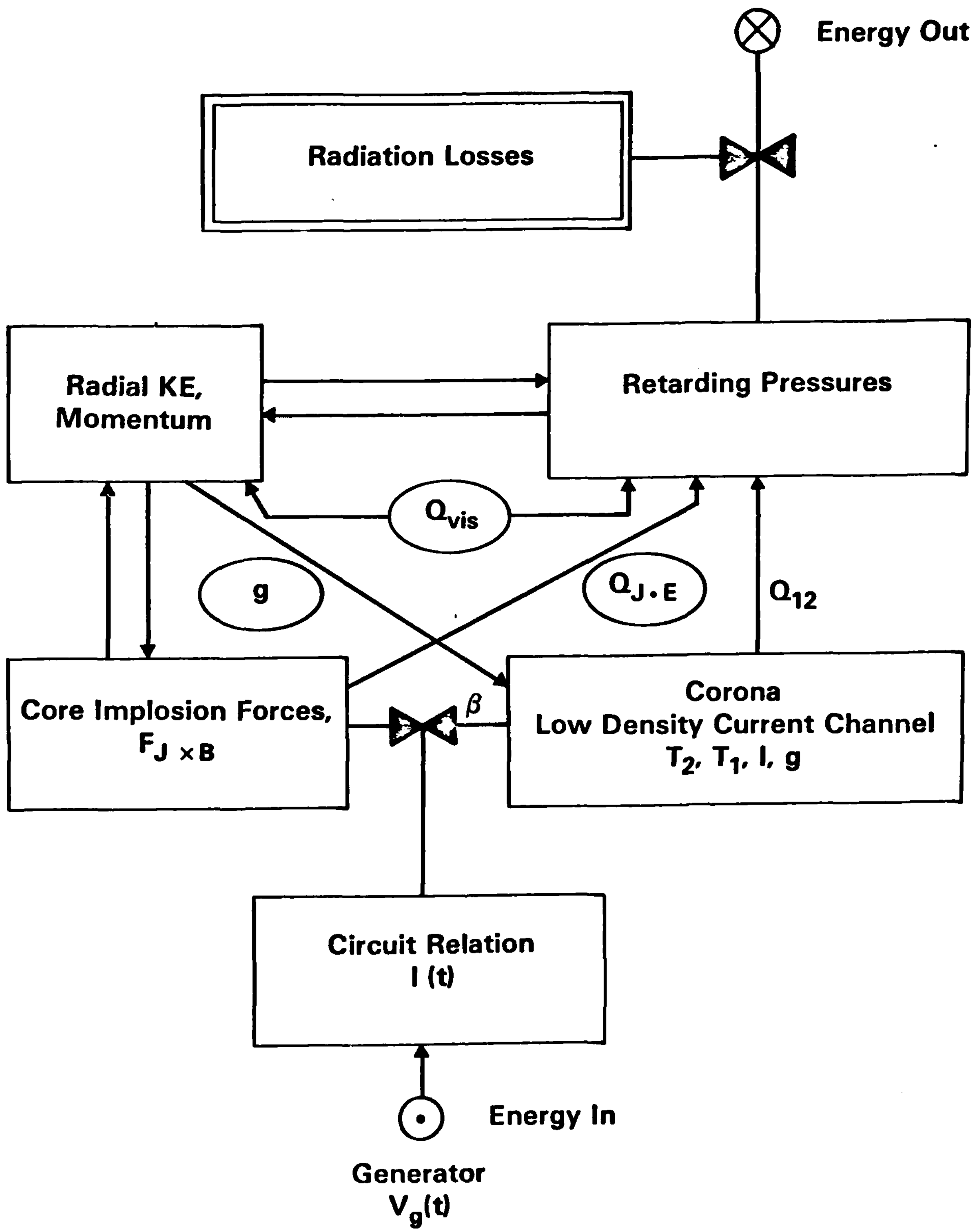
1D • Simple

2D • Hot Spot (Sausage Instability)

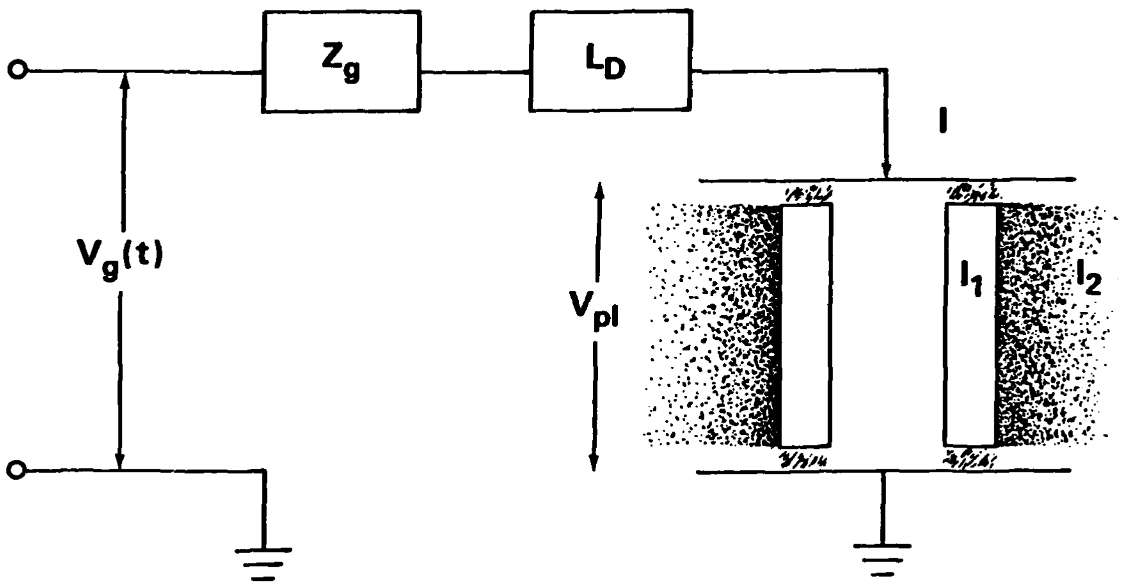
3D • Ribbon (Kink Instability)

- Requires Most Detailed Treatment of Plasma Dynamics and Radiation

Dynamics in the Simple Model



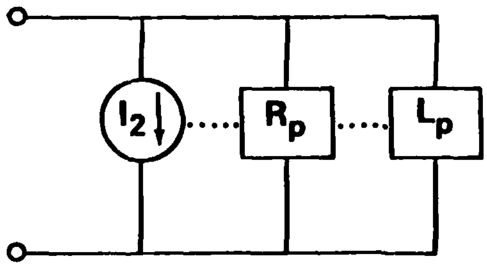
Effective Circuit Relation



I_1 Flows in a Classically Resistive Region $\quad j = \sigma E$

I_2 Flows in a Drift Speed Limiting Region $\quad j = en_eC_s(T_2)$

The Circuit Element Replacing V_{pl} is Like



With the Current Source $I_2(t)$ Controlling the Inductance and Resistance Values.

II. CORONA EVOLUTION:

ASSUME A MARGINALLY STABLE, DRIFT-SPEED LIMITING SYSTEM IN AN AVERAGED STATE OF PRESSURE BALANCE -

$$\nabla\left(n_e(r)\left[T_2 + Z_2^{-1} T_I\right]\right) = c^{-1} J_Z(r) \times B_\theta(r)$$

$$\left|J_Z(r)\right| = n_e(r)\, e\, c_2(T_2)$$

FOR THE ISOTHERMAL SYSTEM, T_2 AND $J_Z(a)$ DETERMINE

$$\left\{ B_\theta(r),\ n_e(r),\ I = I_1 + I_2 \right\}$$

UNIQUELY.

$$\beta \equiv \frac{I_1}{I} = \left[1 - \beta_o + (g\beta_o/2)^2\right] - g\beta_o/2$$

$$n_e(r) = n_a\left(\frac{r}{a}\right)^{\eta-2}\left[\frac{1+\delta}{(r/a)^\eta + \delta}\right]^2$$

WHERE

$$n_a \equiv I_1 / e\pi c_2 (a^2 - r_i^2)$$

$$g \equiv (r_i/a)^2 / (1 - (r_i/a)^2)$$

$$\beta_o \equiv 2c^2 T_2 / e c_2 I .$$

IF $I(t)$, $g(t)$ ARE GIVEN, ONE NEEDS ONLY

$$\frac{d}{dt}(N_2 Z_2 T_2) = I(1-\beta)E_Z + Q_{12} - Q_{rad} - Q_{end} ,$$

$$\frac{d}{dt}(N_2) = F_{12} \cdot Z_1^{-1} \qquad \text{(EFFECTIVE ION EXCHANGE RATE)}$$

WITH Q_{12}, F_{12} EVALUATED BY MEANS OF A SIMPLE KROOK MODEL IN THE TWO REGIONS,

$$Q_{12} = 5\pi a v_t T_e \left[\frac{n_e T_e}{2^{3/2} m_e}\right]^{1/2} \left\{ \frac{\tau_{ee}(-\partial_r \ln n_e)}{1 + (\Omega_a \tau_{ee})^2} - \frac{\tau_{ew}(\partial_r \ln n_e + 4\partial_r \ln T_e)}{1 + (\Omega_a \tau_{ew})^2} \right\}$$

$$F_{12} = \pi a v_t \cdot \left[\frac{n_e T_e}{2^{3/2} m_e}\right]^{1/2} \left\{ \frac{\tau_{ee}(-\partial_r \ln n_e)}{1 + (\Omega_a \tau_{ee})^2} - \frac{\tau_{ew}(\partial_r \ln n_e + \partial_r \ln T_e)}{1 + (\Omega_a \tau_{ew})^2} \right\}$$

IN ORDER TO ADVANCE THE COMPLETE CORONA IMPLICITLY FROM ONE PRESSURE BALANCE TO THE NEXT.

III. CORE PLASMA EVOLUTION

A. STRONGLY-COUPLED PLASMA

SPITZER'S PARAMETER $\ln \Lambda_{ii} = 23 - \ln\left[\sqrt{2 n_i}\, Z^3 (T_e)/T_i^{3/2}\right]$

$(T_i,\ T_e \text{ in eV},\ \ n_i \text{ in cm}^{-3})$

- INITIALLY $T_i \approx 15\,\text{eV}$, $z \approx 3$, $3 \times 10^{18} \leq n_i \leq 1.2 \times 10^{9}$

$$\ln \Lambda_{ii} \approx 2.14 \rightarrow 1.45$$

- TYPICAL PEAK COMPRESSION: 750 eV, $z \approx 10$,

$(1 \rightarrow 4) \times 10^{19}$ CM^{-3} :

$$\ln \Lambda_{ii} \approx 3.8 \rightarrow 3.1$$

- LATER COLLAPSE PHASE: 30 eV, $z \approx 4$, $(1 \rightarrow 4) \times 10^{20}$:

$$\ln \Lambda_{ii} \approx 0.6 \rightarrow -0.12$$

CLASSICAL TRANSPORT APPLIES TO PLASMA WITH $\ln \Lambda_{ii} \gtrsim 10$.

<u>ALTERNATIVE:</u> DISSIPATIVE PROCESSES DOMINATE FLUID EVOLUTION:

(I) RAPID THERMAL CONDUCTION $\longrightarrow \nabla T_i \approx 0$

(II) RAPID THERMAL EQUILIBRATION $\longrightarrow T_e \approx T_i$

(III) RAPID VISCOUS MOMENTUM TRANSFER $\longrightarrow \nabla(\nabla \cdot v) \approx 0$

(IV) RAPID RADIATIVE DIFFUSION $\longrightarrow \nabla(n_i^*/n_i) \approx 0$

RESULT: SIMPLIFIED RADIATION/HYDRO, USEFUL MODEL WHERE CLASSICAL THEORY INAPPLICABLE

B. INITIAL CONDITIONS:

- CHOOSE COMPATIBLE WITH (I - IV).
- CURRENT IN OUTER PART OF CORE: (r_I, a)
- $\nabla n_i / n_i \propto J_z \times B_\theta / n_e(r) - \alpha V(r)$
- $V(r) = G_1 r + G_{-1} r^{-1}$

(THESE PROFILES REMAIN SELF-SIMILAR IN SLAB-GEOMETRY EXPANSION, COMPRESSION AND TRANSLATION, PROVIDED $E_Z(r,t)$ HOLDS $J_Z/e n_e = V_d$ CONSTANT.)

PARAMETER α CONTROLS DV_r/Dt AT t_0.

EVOLUTION WITHOUT EXTERNAL STRESS: $DV_r/Dt = \alpha(t) V_r$ TO GIVE VISCOUS STRESS RELAXED TO ZERO.

(DENSITY MAXIMUM STATIONARY IN THIS CASE, WHILE PROFILE EXPANDS SUBJECT TO BOUNDARY CONDITIONS AT a & b - WHERE ∇p MOVES PLASMA.)

C. RESPONSE TO EXTERNAL FORCES

- TRANSMISSION OF STRESS FROM CURRENT-CARRYING LAYER TO INTERIOR FLUID: $\rho E_r + c^{-1} J_z \times B_\theta + f_{visc}$.

E_r, f_{visc} ARISE IN MAINTAINING $\nabla \cdot V$ HOMOGENEOUS

- Classical plasma can snowplow; strongly-coupled viscous plasma erases inhomogeneous compressions and absorbs momentum over entire volume.

- Simplest model: outer-surface stresses are transmitted unattenuated into plasma. Viscous reaction forces 'instantaneously' redistribute momentum to keep $\nabla(\nabla \cdot v) = 0$

- Simple representation of model: focus on density max (r_m) and inner radius (b), where effective stresses are known:

$$\ddot{r}_m = \left(J_z \times B_\theta \big|_a \right) / c\,\tilde{m}\, n_e(r_m)$$

$$\ddot{b} = -\frac{\tilde{T}}{\tilde{m}} \frac{\nabla n}{n}\Big|_b$$

- Homogeneity of $\nabla \cdot v$ then requires

$$\dot{a} = \dot{r}_m \left(\frac{r_m}{a}\right)\left(1 + \frac{a^2 - r_m^2}{r_m^2 - b^2}\right) - \dot{b}\left(\frac{b}{a}\right)\left(\frac{a^2 - r_m^2}{r_m^2 - b^2}\right)$$

and gives $Dv_r/Dt = \alpha_1 (v_r - \dot{r}_m) + \alpha_0$

D. Assembly on Axis:

Strong ∇n, ∇v

Interpenetrating strongly-coupled fluids

Microturbulence

$\longrightarrow$

Fluid mixing

Dissolution of ∇n & ∇v

Thermalization of flow kinetic energy

USE SIMPLE "COLLECTION" MODEL:

(1) INSIDE A "COLLECTION RADIUS" r_c , THERMALIZE ANY FLOW ENERGY IN EXCESS OF THAT IN STAGNANT FLOW ($v_r = \frac{r}{a}\dot{a}$)

(2) WHEN PARTICLES COLLECTED WITHIN r_c ARE NUMEROUS ENOUGH TO ERASE OR REVERSE ∇n AT r_c , MOVE r_c OUTWARD ONE GRID CELL.

(3) CONTINUE DOING (2) UNTIL r_m MEETS r_c

(4) CONTINUE COMPRESSION OF UNIFORMLY-FILLED CENTER ($r < r_c$)

E. MOTION OF THE COLLECTED PLASMA

- SIMPLE REPRESENTATION OF STRESS TRANSMISSION

$$\ddot{r}_m = \frac{2\tilde{T}}{\tilde{m}\, r_m} - \frac{J_z \times B_\theta \big|_a}{c\tilde{m}\, n_e(r_m)} \quad \text{(EXPLICIT PRESSURE DIFFERENCE)}$$

$$\ddot{a} = \ddot{r}_m \frac{a}{r_m} \quad (\nabla \cdot v \text{ HOMOGENEITY})$$

- SELF-SIMILARITY OF $v(r)$ MAINTAINED BY

$$\frac{Dv(r)}{Dt} = \alpha\, v(r)$$

FROM VISCOUS RESPONSES RATHER THAN FROM A PRESCRIBED PRESSURE GRADIENT.

F. Core Energy Transport (spatially integrated)

$Z(T_e)$ ASSUMED

$$\frac{d}{dt}(Z_1 T_1) = \frac{2 A m_p}{3\pi(a^2 - b^2)\rho}\Big\{ Q_{pdV} + Q_{visc} + Q_{ohmic} + \pi(a^2 - b^2)\left(\frac{3 m_e n_1}{A m_p \tau_e}\right)(T_I - T_1) + Q_{12} + P_{rad}\Big\}$$

$$\frac{d}{dt} T_I = \frac{2 A m_p}{3\pi(a^2 - b^2)\rho}\left\{ Q_{pdV} + Q_{visc} + \pi(a^2 - b^2)\left(\frac{3 m_e n_1}{A m_p \tau_e}\right)(T_1 - T_I)\right\}$$

WITH Q_{12} THE CORE/CORONA INTERFACE HEAT EXCHANGE,

Q_{VISC} CALCULATED FOR THE VELOCITY FIELD $V_R(a, b, \dot{a}, \dot{b})$,

P_{RAD} A COMBINATION OF LINE, RECOMBINATION AND BREMSSTRAH-LUNG.

G. External Circuit

$E_Z = V_{PLASMA} \ell^{-1}$ IN THE CORONA REGION

$\eta_\perp J(a) = E(a) + c^{-1} \dot{a} (\hat{r} \times B_\theta)_a$ ON CORE/CORONA INTERFACE.

FROM FARADAY'S LAW

$$V_{PLASMA} = I\,R^{*} + \frac{2\ell}{c^2}\frac{d}{dt}\left[\int_a^{r_w} dr_1\,\frac{I(r_1)}{r_1}\right]$$

AND INCLUDING THE BALANCE OF THE CIRCUIT

$$V_g(t) = IZ_g + \dot{I}L_d + IR^{*} + \frac{d}{dt}\left[\frac{2\ell I}{c}\ln\frac{r_w}{a} - \frac{\ell}{c}\alpha\ln(1+\delta)\right]$$

WITH

$$R^{*} \equiv \ell\beta\left[\frac{\eta_\perp}{\pi(a^2 - r_1^2)} - \frac{2\dot{a}}{c^2 a}\right],$$

β, α, δ CORONA PARAMETERS.

GIVEN $I(t)$, $V_g(t)$, $a(t)$, $\eta_\perp(t)$, AND THE CORONA PARAMETERS THE EXPLICIT DERIVATIVE $\dot{I}(t)$ IS CALCULATED.

H. TRACKING THE DENSITY PROFILE

LET $\mathcal{V}(t) \equiv \pi\ell\left[a^2(t) - b^2(t)\right]$, AND IF

$$\nabla(\nabla\cdot v) = 0 \quad \& \quad r_0 = r(t) + \int_t^{t_0} dt_1\, v(r(t_1), t_1)$$

THEN

- $n(r(t), t) = n(r_0, t_0)\exp - \int_{t_0}^{t} dt_1 (\nabla\cdot v)[r_1(t_1), t_1]$

OR $\dfrac{n(r,t)}{n_0(r_0,t_0)} = \dfrac{\mathcal{V}(t_0)}{\mathcal{V}(t)}$.

- ANY $n(r_0, t_0)$ CAN BE EVOLVED BY FOLLOWING $r(t, r_0)$.

IV. RADIATIVE LOSSES

FOR DIAGNOSTICS, DIVIDE INTO

- LOW ENERGY LINES ($h\nu < 1\text{keV}$)
- HIGH ENERGY LINES ($h\nu > 1\text{keV}$)
- CONTINUUM (RECOMB. AND BREMSS.)

USE CURVE FIT TO CRE MODEL OF DUSTON AND DAVIS[1] FOR Al. (THIN CYLINDER, .05 CM RADIUS ELEMENTAL RADIATOR.)

USE APRUZESE PROBABILITY-OF-ESCAPE[2] TO FURTHER ATTENUATE EACH SPECTRAL CATEGORY.

INTEGRATE RADIATIVE LOSS OVER THE DENSITY PROFILE.

V. TYPICAL IMPLOSION TRAJECTORIES

- SIMPLE COLLAPSE (SC)--IMPLOSION HEATING TOO WEAK TO REVERSE RADIAL MOTION. DENSITY PEAK <u>AFTER</u> TEMPERATURE PEAK.

<u>OR</u>

- BOUNCE AND COLLAPSE (BC)--IMPLOSION HEATING HALTS RADIAL MOTION. PLASMA BOUNCES, COOLS, COLLAPSES AGAIN. TEMPERATURE AND DENSITY PEAKS CLOSER TOGETHER

<u>OR</u>

- Pause and Collapse (PC)--on the dividing line between SC and BC. Plateau in density, then further compression.

- Bounce and Dissipate--Not seen for the driving voltage waveforms used. Radiative losses prevent this trajectory.

- The typical initial condition is shown

$$\left[\begin{array}{l} r_m^0 \sim 0.96 \\ g(r_I, a) \sim 9.0 \\ T_i(0) \sim 15\,\mathrm{eV} \\ 7.5\times 10^{18}\ \mathrm{Al}\ \text{ATOMS} \end{array}\right.$$

- SC and BC Implosions: Figure shows Lagrangian zones

$$[b(t) < r_1(t) < r_m(t) < r_2(t) < a(t)]$$

AVERAGE DENSITY

$$\overline{n_i}(t)$$

ION TEMPERATURE

$$T_i(t)$$

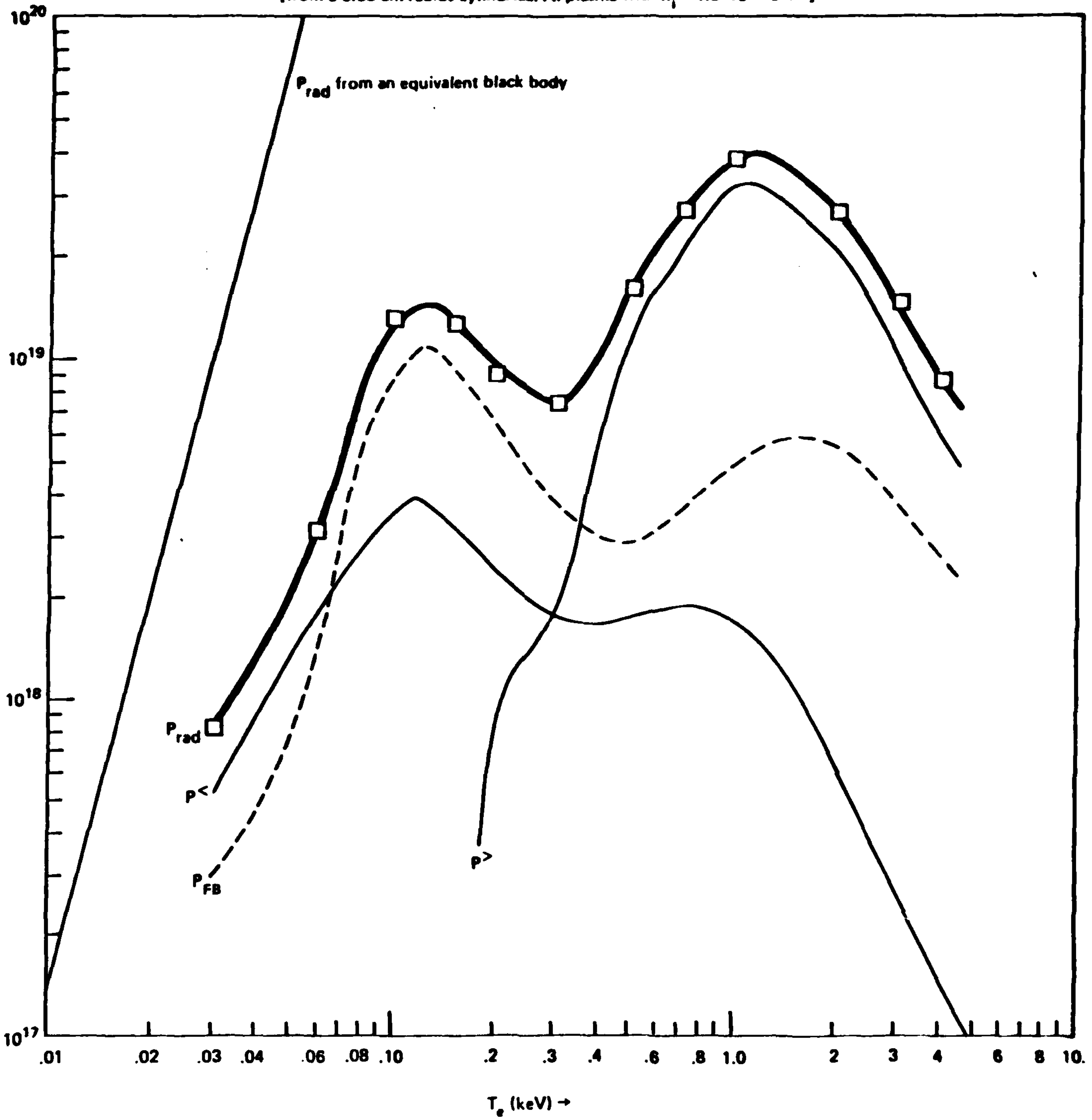
As Functions of

t in arbitrary units, with <u>early</u> density values shown for each zone.

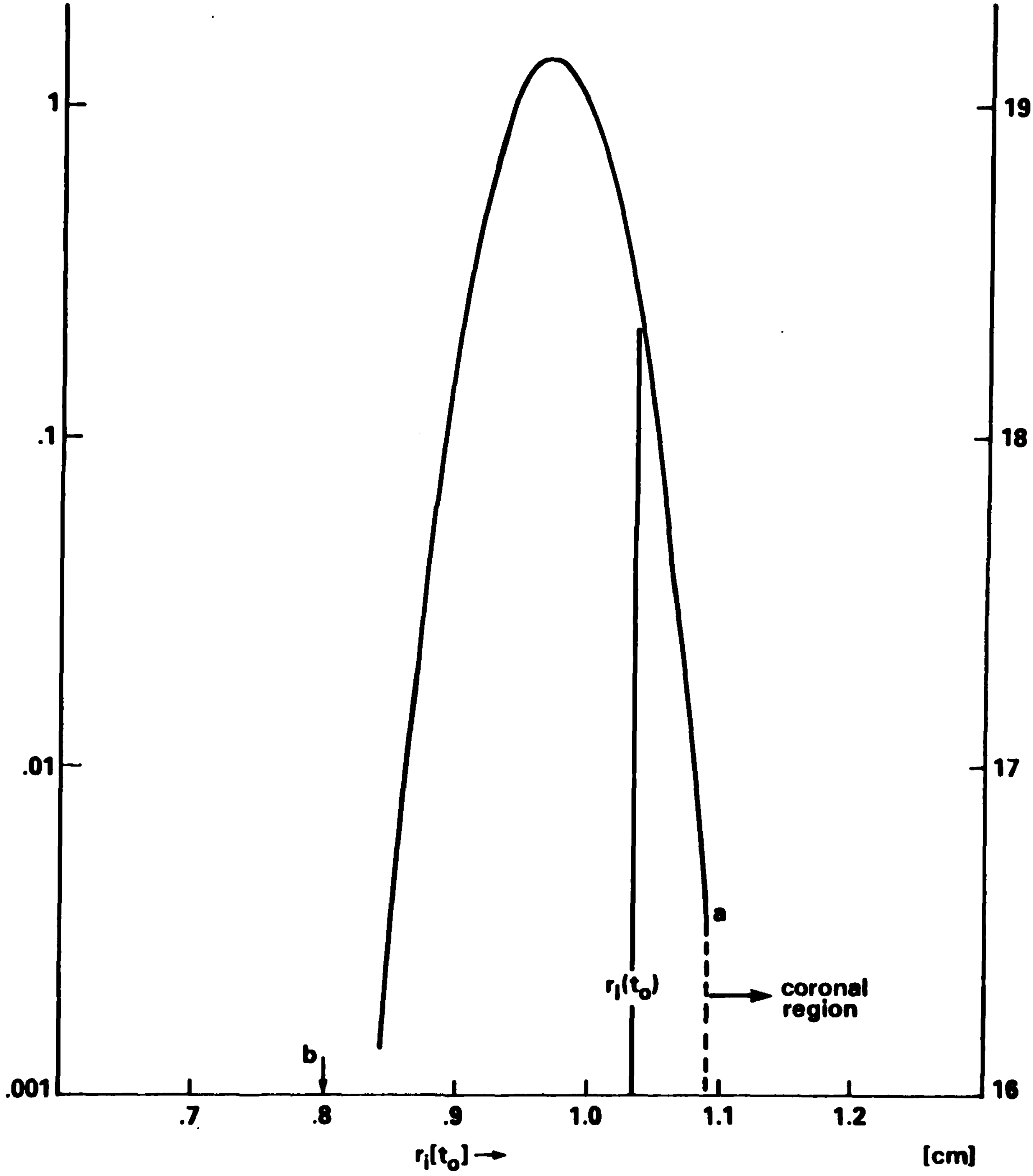
- A sequence of BC density profiles, (N) denotes the number of time steps.

P_{rad} (erg/cm^3 sec) as a function of T_e (keV)

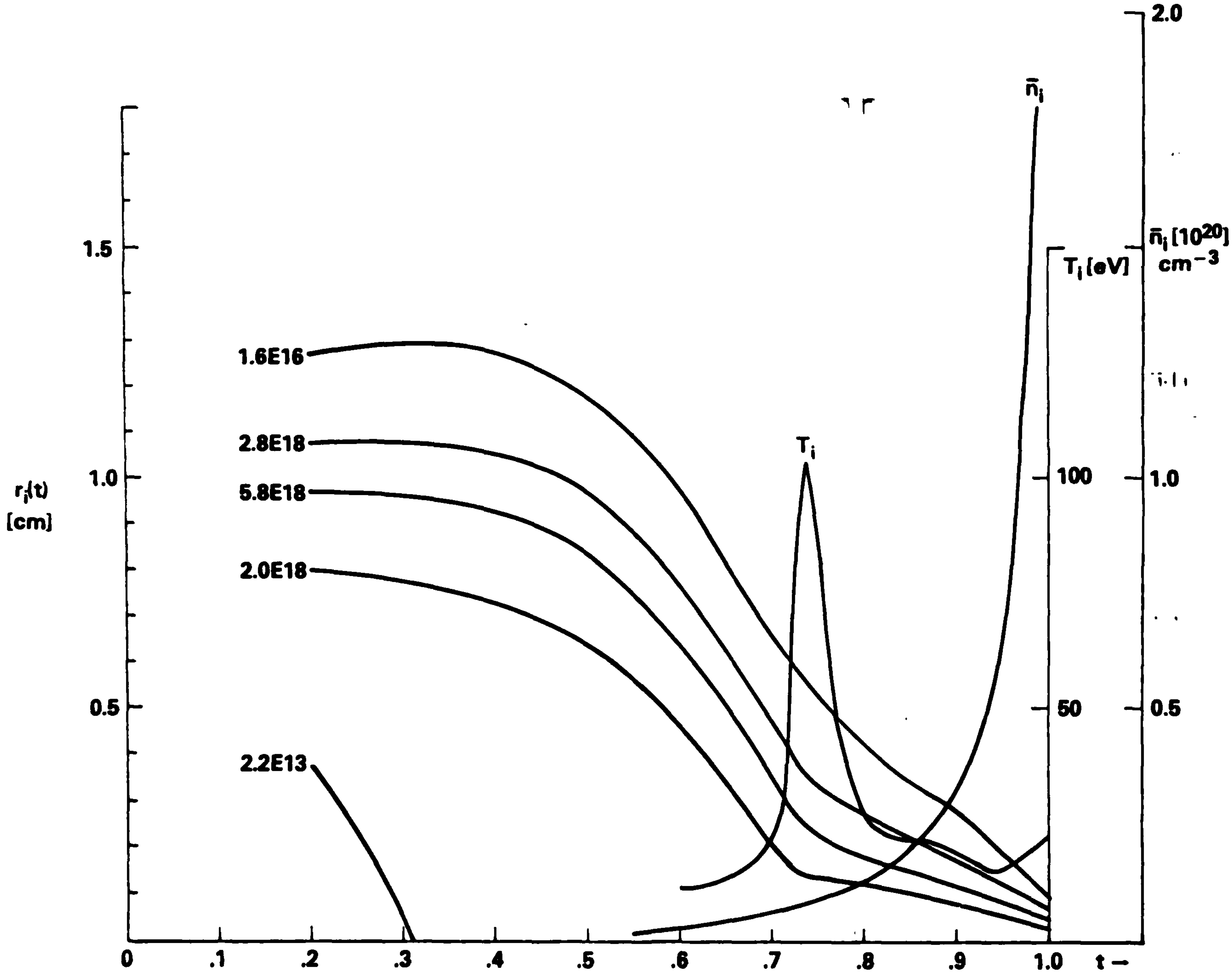
[from a 0.05 cm radius cylindrical Al plasma with $n_i = 1.0 \cdot 10^{19}$ cm^{-3}]



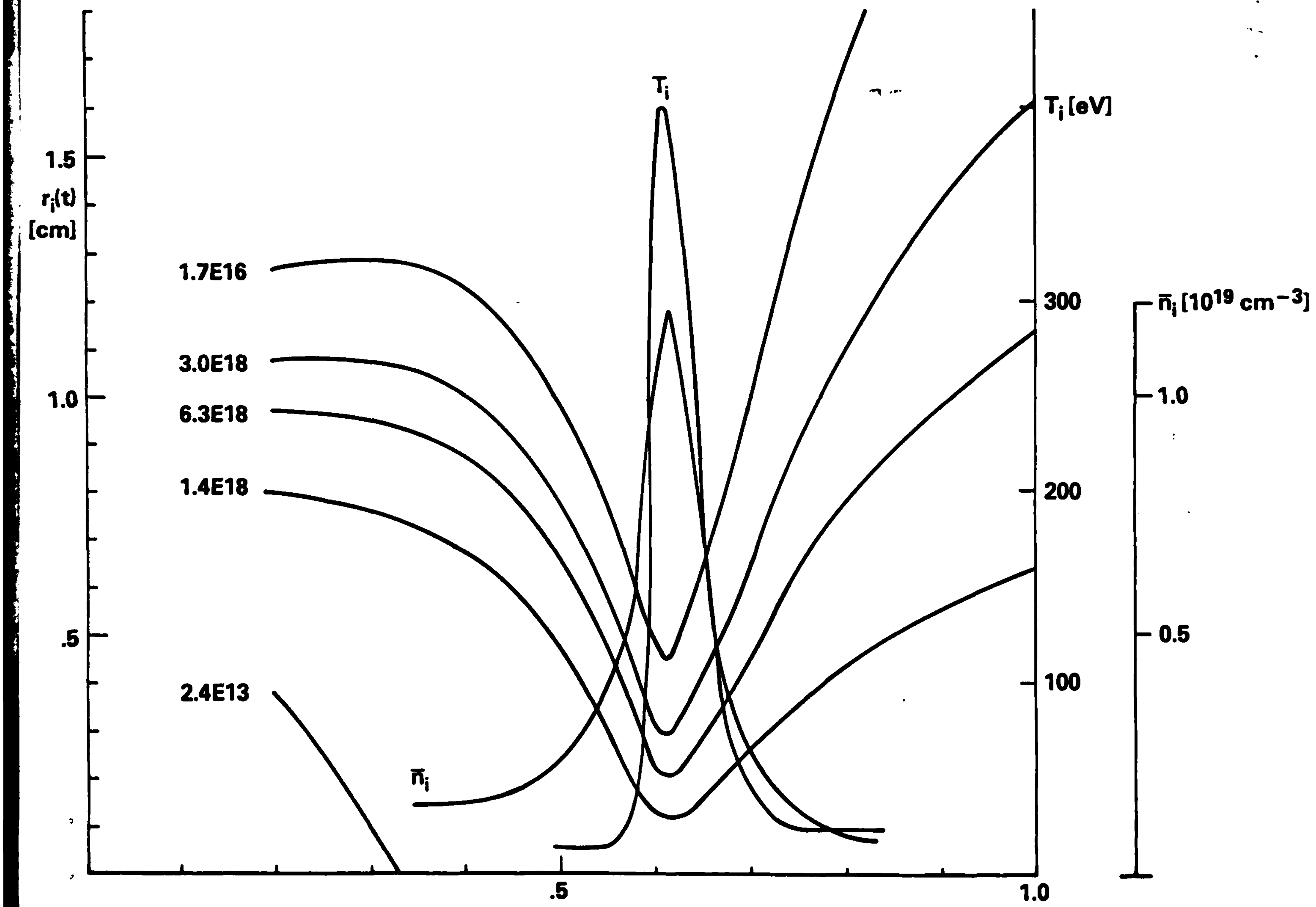
Initial Density Profile: $n_i(r_i[t_o]),[10^{19}\ cm^{-3}]$



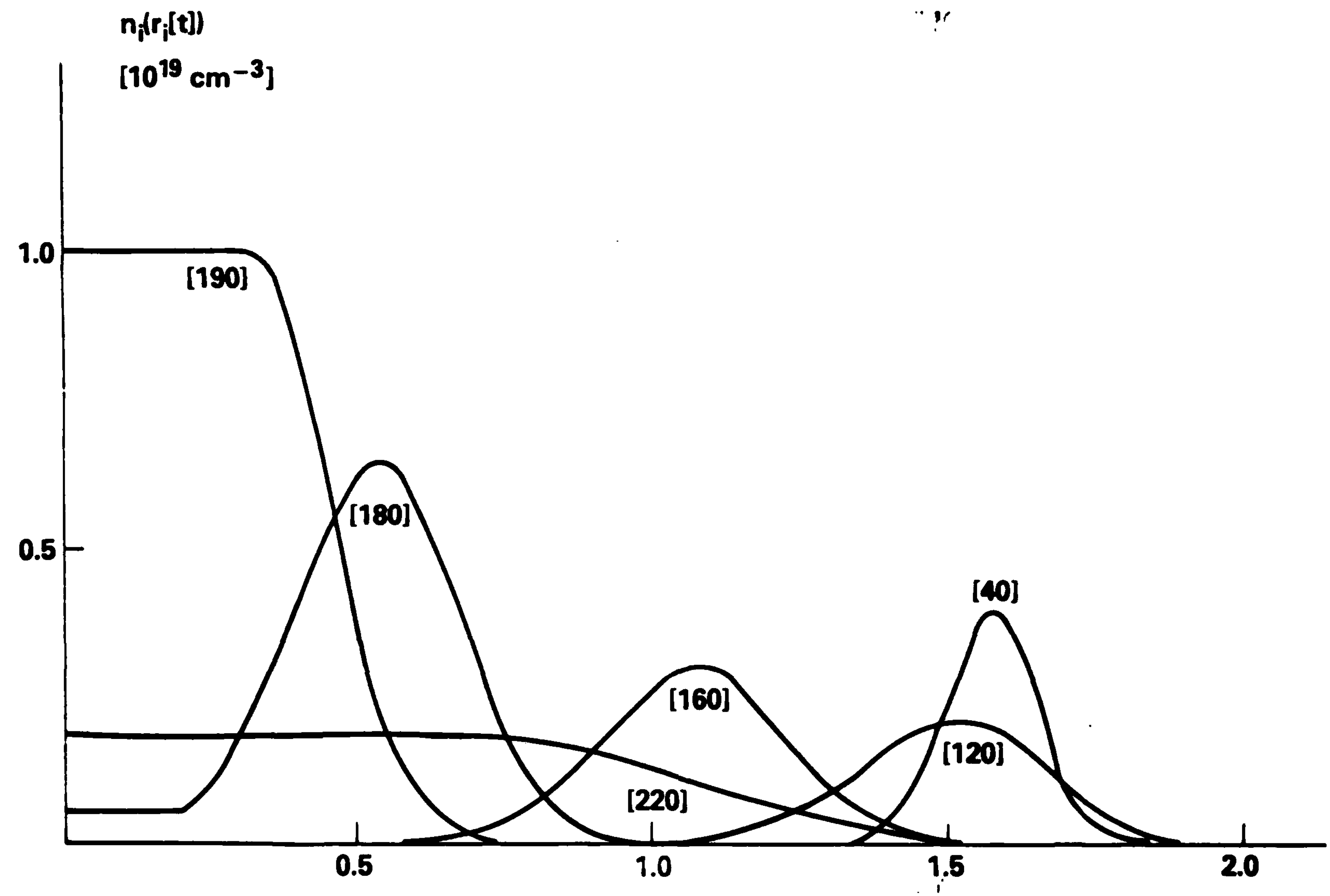
Simple Collapse Implosion



Bounce and Collapse Implosion



Radial Profiles of a Bounce and Collapse Implosion [xxx] Time Sequence



VI. GENERATOR AND LOAD COUPLING

AS A GENERAL MEASURE OF IMPLOSION PERFORMANCE, DEFINE

$$\mathring{T}_i \equiv \sup_{0<t<t_{max}} T_i(t)$$

OVER THE TIME SCALE t_{MAX} CHARACTERISTIC OF A SINGLE COMPRESSION AND SUBSEQUENT EXPANSION OF THE LOAD.

IN THE FIGURE BELOW THIS PARAMETER IS SHOWN AS A FUNCTION OF :

R_M^0 - INITIAL DENSITY PROFILE PEAK (LOAD RADIUS)

V_{GEN} - PEAK GENERATOR VOLTAGE

g^0 - INITIAL CURRENT PENETRATION PARAMETER

M_0 - TOTAL MASS OF THE LOAD

AND THE COMMON CASE AMONG THESE FIGURES IS

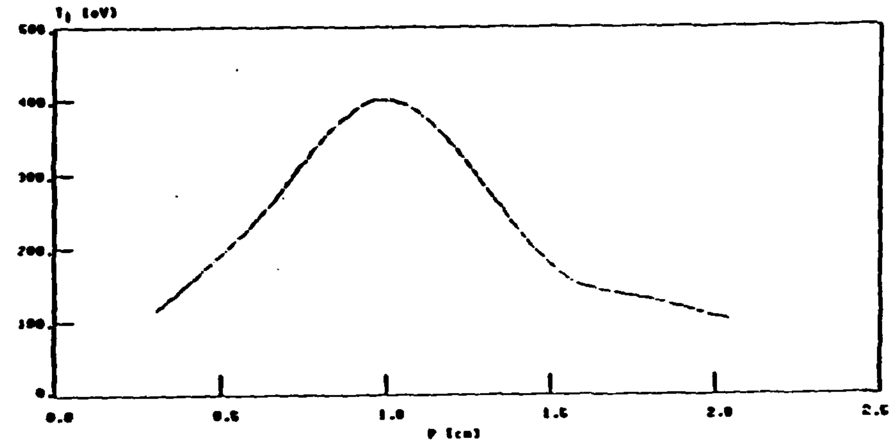
$R_M^0 \approx 0.96$ (CM)

$V_{GEN} = V_0$ (ARBITRARY UNITS)

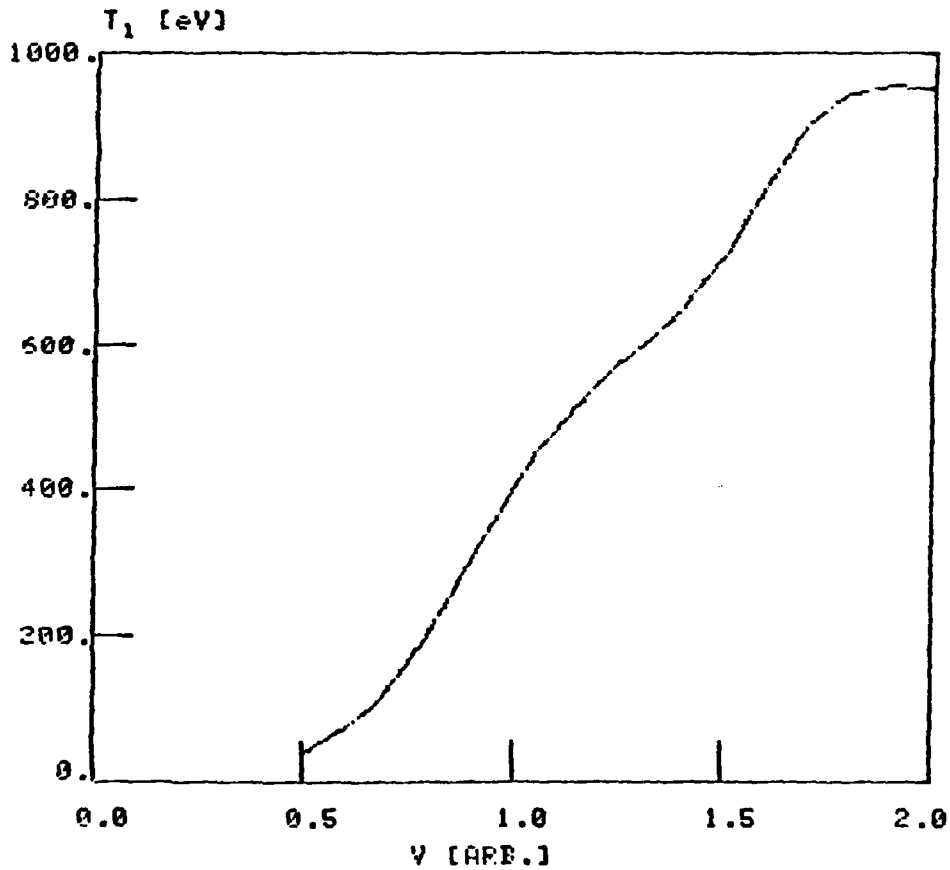
$g^0 = 9.0$

$M_0 = 12$, 1.5 MIL Al WIRES (7.51×10^{18} ATOMS OF Al)

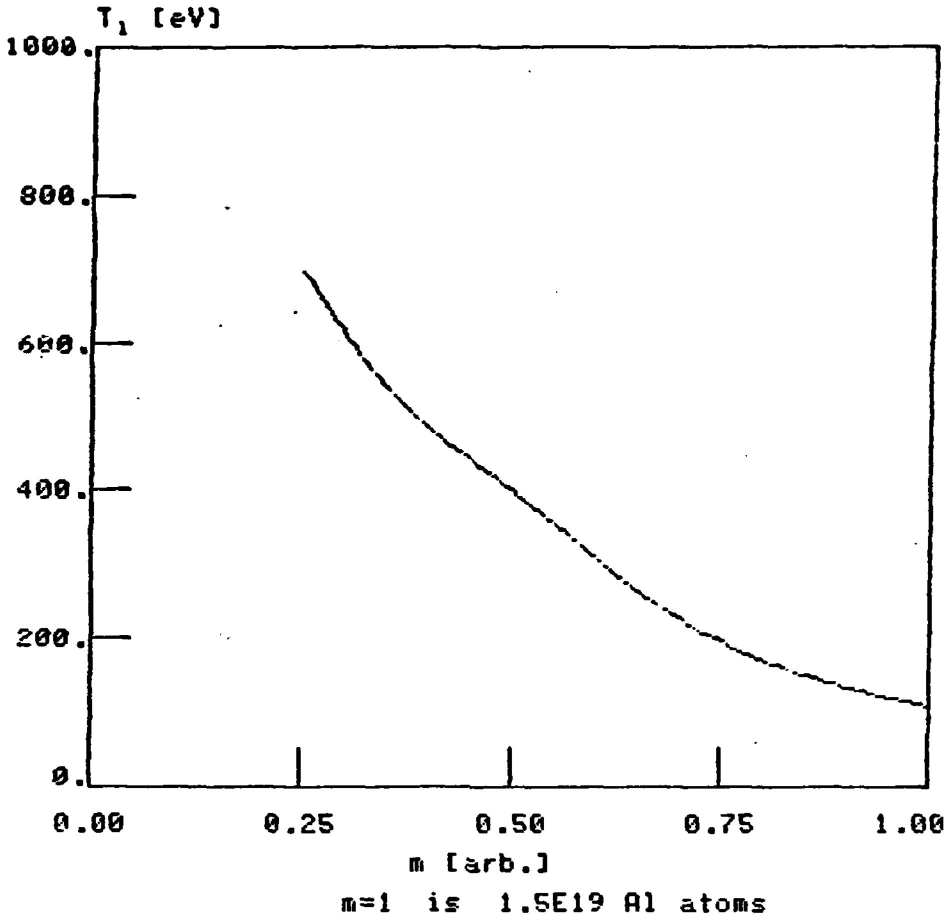
THE ABSOLUTE LOCATION OF THESE CURVES IS SENSITIVE FUNCTION OF THE CURRENT PENETRATION PARAMETER g^0, WHICH EFFECTIVELY SETS A "MEAN SKIN DEPTH" FOR THE ELECTROMAGNETIC FIELD PENETRATION OVER THE IMPLOSION HISTORY.

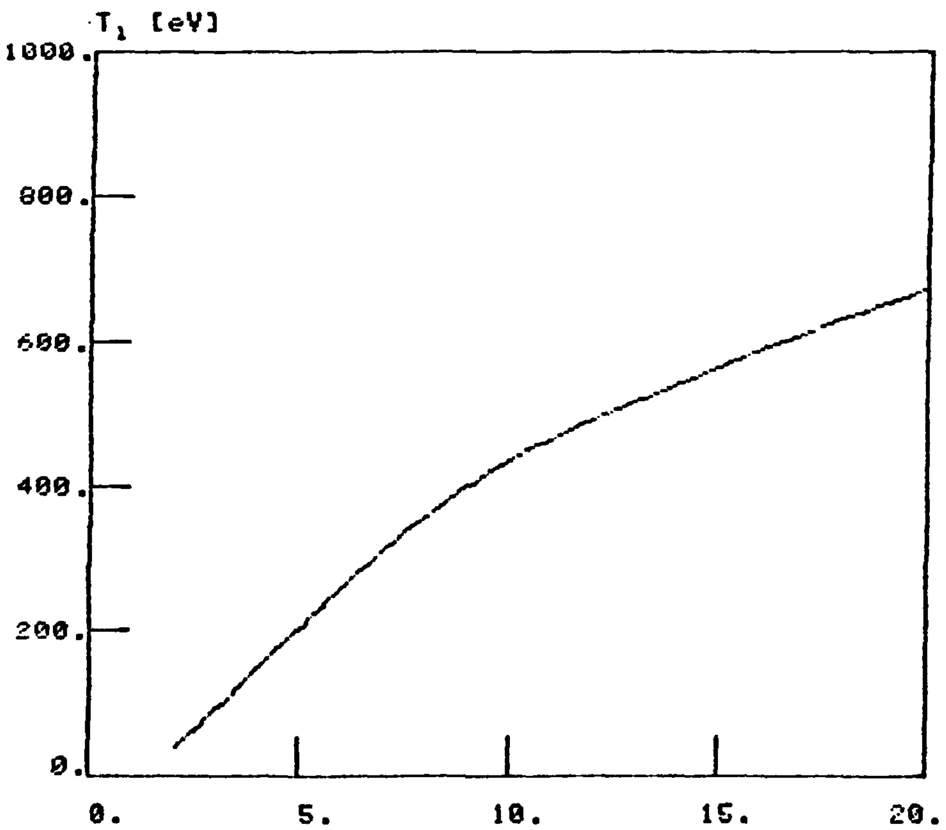


500.
400.
300.
200.
100.
0.
0.0
0.5
1.0
1.5
2.0
2.5



T_1 [eV]
1000.
800.
600.
400.
200.
0.
0.0
0.5
1.0
1.5
2.0
V [ARB.]


T₁ [eV]
1000.
800.
600.
400.
200.
0.
0.00
0.25
0.50
0.75
1.00
m [arb.]
m=1 is 1.5E19 Al atoms


T₁ [eV]
1000.
800.
600.
400.
200.
0.
0.
5.
10.
15.
20.

VII. CONCLUSIONS

THE IMPLOSION DYNAMICS ARE DOMINATED BY THE AMOUNT OF ENERGY DELIVERED BY THE GENERATOR TO THE RADIAL FLOW OF THE FLUID LOAD.

- FOR LOW VALUES OF THIS ENERGY, THE HEATING ON ASSEMBLY IS TOO WEAK TO REVERSE THE IMPLOSION, AND A REFRIGERATION (SC) OCCURS, WITH THE PEAK COMPRESSION AFTER THE PEAK TEMPERATURE.
- AS DELIVERED ENERGY IS INCREASED, THE COMPRESSION PEAK AND ASSEMBLY-HEATING TEMPERATURE PEAK BECOME CLOSER IN TIME. ASSEMBLY HEATING AND COMPRESSION HEATING WORK TOGETHER TO PRODUCE HIGHER PEAK TEMPERATURE.
- IN CONTRAST, WHEN <u>FURTHER</u> FLOW ENERGY IS GIVEN TO THE LOAD, THE ASSEMBLY HEATING TENDS TO HALT THE COMPRESSION VERY RAPIDLY (AND AT A LARGER RADIUS) AND THE COMPRESSION REVERSES <u>TOO SOON</u>. THIS RESULTS IN A LOWER PEAK TEMPERATURE.

ALL THESE EFFECTS ARE SUPERIMPOSED ON A VERY SENSITIVE COUPLING TO THE CORONAL REGION, AS MEASURED IN PART BY THE RELATIVE SKIN DEPTH PARAMETER g. AS THE CURRENT IS FORCED TO A THIN LAYER ($g \to \infty$) THE SURFACE STRESSES ON THE CORE PLASMA BECOME STRONGER UNTIL VERY LARGE g VALUES DEMAND THAT $\beta \to 0$ AND FORCE MOST OF THE CURRENT TO THE CORONA. AS $g \to 0$ THE CORONA BECOMES RELATIVELY UNIMPORTANT AND THE SURFACE STRESSES WEAKEN. AN ACCURATE ASSESSMENT OF THE IMPORTANCE OF TURBULENT CURRENT TRANSPORT IN THE LOW DENSITY REGIONS OF THE ANNULAR LOAD MUST THUS DEPEND UPON A PROPER ELECTROMAGNETIC TREATMENT OF THE E_r, E_z AND B_θ FIELD[3] PROFILES WITHIN THE LOAD. THIS IS A SUBJECT OF FURTHER WORK AND THE OUTCOME WILL PROVIDE A FIRST-PRINCIPLES GUIDE TO THE APPROPRIATE g VALUES FOR THIS SIMPLE MODEL.

REFERENCES

1. D. Duston and J. Davis, Phys. Rev. A, 21, May 1980.

2. J. Apruzese and J. Davis, "Direct Solution of the Equation of Transfer Using Frequency-and-Angle-Averaged Photon Escape Probabilities." NRL Memo Report Number 4017, 21 June 1979.

3. R. E. Terry and J. U. Guillory, JAYCOR Report Number TPD200-80-012, October 1980.

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